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MHD Equilibrium Property with Bootstrap Current in Heliotron Plasmas

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Abstract

We study the properties of MHD equilibrium with self-consistent bootstrap current for a heliotron type device. We show the possibility that MHD equilibrium beta limit with consistent bootstrap current might significantly decrease in the low collisional regime comparing with currentless case depending on the vertical field control methods in finite beta and magnetic configurations.

Keywords:

heliotron, bootstrap current, MHD equilibrium, low collisional regime, boundary condition

1. Introduction

The neoclassical theory of stellarators predicts the existence of the bootstrap current particularly for rare collisional plasmas[1]. We already studied the effect of bootstrap current on the finite beta MHD equilibrium including bootstrap current in the $1/\nu$-regime[2] and also studied the collisionality and radial electric field effect on the bootstrap current and consistent MHD equilibrium[3] under the fixed-boundary condition.

Here we mainly concern the effect of the vertical field control methods in finite beta plasma on the bootstrap current and consistent MHD equilibrium. We apply the VMEC code[4,5] to calculate the 3D MHD equilibrium. It is hard to decide the outermost magnetic surface under the free-boundary condition. It is well known that the torus outward shift of outermost magnetic surface destroys the peripheral magnetic surface and Pfirsch-Schlüter current itself does so. Here we apply two ways to decide outermost plasma surface. One way is to keep the toroidal flux surrounded by outermost magnetic surface as same as vacuum. Another way is to keep the position of outermost magnetic surface at torus outside as same as vacuum, which leads to the reduction of plasma volume in finite beta[6]. This way is based on the analysis for vacuum magnetic field feature in peripheral region[7] and by using HINT code[8]. It should be noted that we dont apply the vertical field control as to keep the toroidally averaged position of outermost magnetic surface as same as vacuum. According to Ref.[6], such results are almost the same as the fixed-boundary case. We obtain almost the same results about bootstrap current and the position of magnetic axis and outermost magnetic surface in two ways to decide the plasma boundary. We show the results for latter way in this paper.

2. Finite Beta MHD Equilibrium with Self Consistent Bootstrap Current

We have studied the property of MHD equilibrium with self-consistent bootstrap current for a device with LHD like configuration. LHD has the following device parameters[9]: $L=2/M=10$, $R_C=3.9$ m, $B_0=3$ T. In this paper, we apply the following assumptions: simple plasma consisting of primary ions and electrons, $Z_{eff}=1$, n_e, T_i, $T_e \propto (1-\psi)$, $<\beta> \approx \beta_0/3$. Here ψ is the normalized toroidal flux.

Magnetic axis positions are different between fixed- and free-boundary case without net toroidal current. However, the shafranov shifts normalized by

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major radius are the same, where we define the shafranov shift as the difference between magnetic axis and the center of the outermost magnetic surface. Figure 1 shows the magnetic axis shift and bootstrap current taking self-consistent bootstrap current into account. The shafranov shift as well as the magnetic axis position itself in free-boundary case is larger than fixed-boundary case though the bootstrap current is almost the same for $\beta_0 \approx 4.5$ %. According to the current density profile data, the bootstrap current density in free-boundary case is smaller than fixed-boundary case in plasma center region because the magnetic axis in free boundary case is located in torus outer region than fixed boundary case. It should be noted that the self-consistent equilibrium with the bootstrap current is obtained by iteratively calculating the bootstrap current density as a function of the flux surface and the finite beta equilibrium with the net toroidal plasma current[2]. The closed circles correspond to the case where we can not get the convergence calculation results. Here bootstrap current flows so that the rotational transform is reduced, which we call negative current. The negative current leads to the larger shafranov shift because rotational transform is reduced. The larger shafranov shift causes larger negative current. Such positive feedback leads to no convergence calculation result, which leads to no existence of MHD equilibrium. This feature is closely related to the dependence of geometric factor $(f_t/f_c)\, G_{bs}{}^{1/\nu}$ on the magnetic axis in heliotron type device. It should be noted that the bootstrap current in the $1/\nu$ regime of stellarators is approximately expressed as[1]

$$\left\langle j_{bs} B \right\rangle \propto \frac{f_t}{f_C}\, G_{bs}^{1/\nu}\, P\Big(\frac{n'}{n} + \alpha_1 \frac{T_i'}{T} + \alpha_2 \frac{T_e'}{T}\Big), \qquad (1)$$

by $(f_t/f_c)\, G_{bs}{}^{1/\nu}$ where α_1 and α_2 are constants on the order of 0.1. f_t/f_C is ratio of trapped and untrapped particles. Figure 2 shows the geometric factor $(f_t/f_c)\, G_{bs}{}^{1/\nu}$ in vacuum field. Here we should notice that it decreases as the magnetic axis shifts torus outward and finally the bootstrap current flows in the direction that leads to reduction of rotational transform. This is common feature in heliotron type devices[1].

Figure 3 shows the magnetic axis shift and self-consistent bootstrap current for fixed-boundary condition with different magnetic configurations. Magnetic axis shift with bootstrap current for $R_{ax}{}^{V} > 3.90$ m (magnetic axis located in torus outward shift) case is smaller than currentless case for $\beta_0 \le 1$ %. On the contrary, for $\beta_0 \ge 1$ % it is larger than currentless case, where bootstrap current flows in the direction that the rotational transform reduces near plasma center. As beta increases more, we can not get the convergence results, either.

From Fig.2, we might consider that $R_{ax} \approx 4.00$ m is the criterion that the consistent MHD equilibrium with

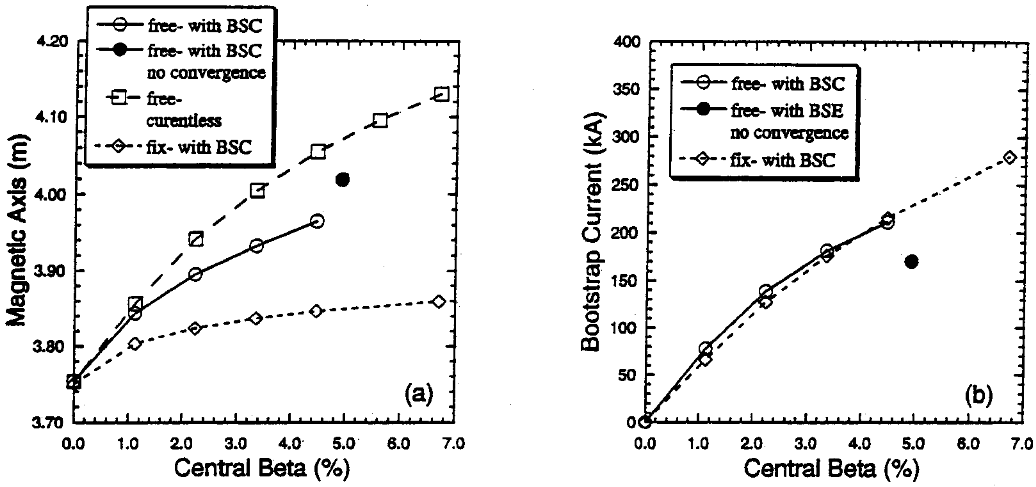

Fig. 1 Dependence of (a) magnetic axis shift and (b) bootstrap current on central beta value. □, ○ (●) and ◇ correspond to the currentless free-boundary equilibrium, free-boundary and fixed-boundary equilibrium with self consistent bootstrap current.

bootstrap current exists for a configuration like LHD. According to the calculation results that the MHD equilibria with consistent bootstrap for $R_{ax}^{V} \leq 3.90$ m have the magnetic axis $R_{ax} < 4.00$ m even in the high beta regime, where MHD equilibria exist. Here R_{ax}^{V} is the magnetic axis position in vacuum.

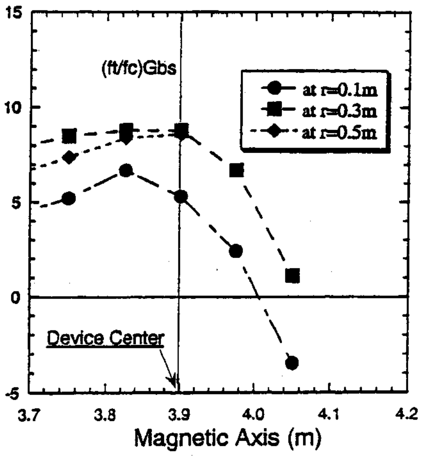

Fig. 2 Dependence of the geometric factor $(f_t/f_c)\,G_{bs}^{1/v}$ in low collisional regime on vacuum magnetic axis position.

3. Discussion

Here we review the effect of the vacuum magnetic field configuration and the pressure profile on the MHD equilibrium properties in heliotron plasma without net toroidal current. Heliotron type devices with planner axes have the following MHD equilibrium features[10].

As beta increases and the shafranov shift increases,

(1) magnetic shear like tokamak appear in plasma center region,

(2) magnetic shear like heliotron is enhanced in plasma peripheral region,

(3) magnetic well is produced in plasma center region.

Here it should be noted that the above MHD features do not change even for the different vacuum magnetic field configurations and the different pressure profiles. It is sure that the quantitative change exists, which leads to the different feature in MHD stability and transport. On the contrary, the heliotron devices with bootstrap current in low collisional regime have other features. Because the bootstrap current is proportional to beta and significantly depends on magnetic axis position.

(I) For magnetic axis located in the less torus-outer region[2]

As beta increases and the rotational transform monotony increases in the whole plasma region,

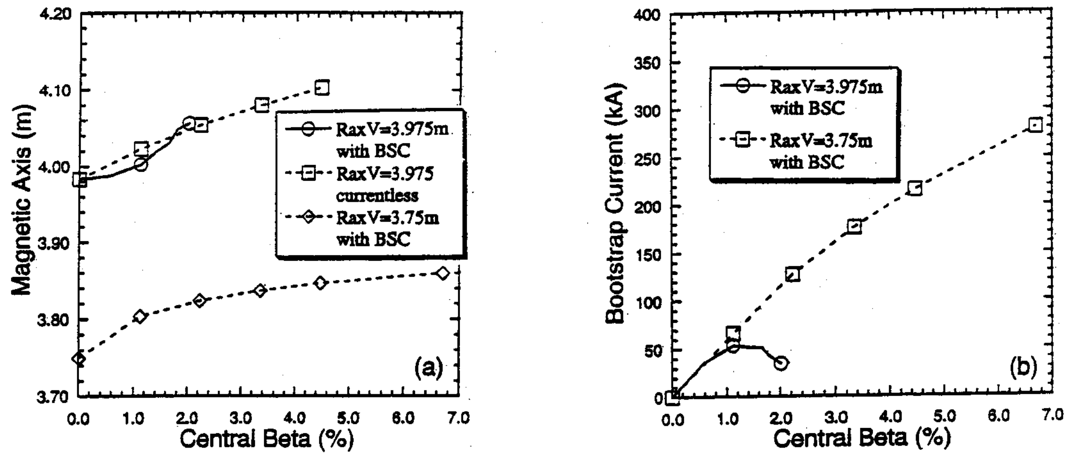

Fig. 3 Dependence of (a) magnetic axis shift and (b) bootstrap current on central beta value for fixed-boundary condition. □, ○ and ◇ correspond to the currentless equilibrium and self-consistent equilibrium with $R_{ax}^{V} = 3.975$ m, and self-consistent equilibrium with $R_{ax}^{V} = 3.75$ m.

(1) magnetic shear like tokamak does not appear in plasma center region,
(2) magnetic shear like heliotron is reduced in plasma peripheral region,
(3) production of magnetic well is suppressed in plasma center region because Shafranov shift is suppressed.

(II) For magnetic axis located in the more torus-outer region

Above a beta value (or a magnetic axis position), consistent MHD equilibrium with bootstrap current, which flows in the direction that rotational transform reduces, does not exist.

Vacuum magnetic field configurations and vertical field control methods in finite beta give the big effect on the magnetic axis location. Then the feature of MHD equilibrium with bootstrap current in low collisional regime changes depending on the vacuum magnetic field configurations and the vertical field control methods in finite beta.

4. Concluding Remarks

We study the properties of MHD equilibrium with self-consistent bootstrap current under fixed- and free-boundary conditions for a heliotron type device (LHD) and in the different vacuum magnetic axis configurations. Here we focus the low collisional regime.

The big difference in free-boundary analyses with bootstrap current is that the MHD equilibrium beta limit significantly reduces comparing with currentless case in the rare-collisional regime. In the fixed-boundary case, the vacuum magnetic configurations with the large torus outward shift of magnetic axis have the same feature.

In the currentless case, the MHD equilibrium features do not change for the different vacuum magnetic field configurations, the different pressure profiles and the vertical field control methods in finite beta. On the contrary, in low collisional regime bootstrap current becomes large to enough to change the MHD equilibrium features. The features of MHD equilibrium with self-consistent bootstrap current change for the different magnetic field configurations and the field control methods because bootstrap current strongly depends on the magnetic axis position in heliotron type devices.

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